US Army Corps
of Engineers
Construction Engineering
Research Laboratory

AD-A241 030

USACERL Special Report N-91/24
September 1991

Modeling Nonlinear Acoustical Blast Waves Outdoors: A Research Summary

by
Victor W. Sparrow

Current techniques for predicting sound propagation outdoors do not accurately model the physics of very loud sounds (over 150 dB), where the mathematics governing the sound propagation become nonlinear. As a result, Army installations need to measure and characterize impulse noises from actual blasts to anticipate environmental impacts of military operations on neighboring communities.

This report summarizes research that developed and verified a numerical method to model nonlinear acoustical blast waves, and investigated the interaction between the finite amplitude blast waves and a natural ground surface. Absorbing boundary conditions were also developed to allow for a numerical solution on a relatively small computational domain. It was determined that, as the finite amplitude effects are increased, the effect of a finite ground impedance is decreased. Since this relationship is itself nonlinear, this implies that the practice of simply adding finite amplitude effects and ground surface effects to find sound levels is not valid. Linear extrapolations and techniques should only be used where linear acoustics are applicable.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	September 1991	Final

4. TITLE AND SUBTITLE

Modeling Nonlinear Acoustical Blast Waves Outdoors: A Research Summary

5. FUNDING NUMBERS

PE 4A161102
PR AT23
WU NN-E30

6. AUTHOR(S)

Victor W. Sparrow

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

USACERL
PO Box 9005
Champaign, IL 61826-9005

8. PERFORMING ORGANIZATION REPORT NUMBER

USACERL SR N-91/24

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of the Chief of Engineers
ATTN: DAEN-ZA
20 Massachusetts Avenue, NW.
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Current techniques for predicting sound propagation outdoors do not accurately model the physics of very loud sounds (over 150 dB), where the mathematics governing the sound propagation become nonlinear. As a result, Army installations need to measure and characterize impulse noises from actual blasts to anticipate environmental impacts of military operations on neighboring communities.

This report summarizes research that developed and verified a numerical method to model nonlinear acoustical blast waves, and investigated the interaction between the finite amplitude blast waves and a natural ground surface. Absorbing boundary conditions were also developed to allow for a numerical solution on a relatively small computational domain. It was determined that, as the finite amplitude effects are increased, the effect of a finite ground impedance is decreased. Since this relationship is itself nonlinear, this implies that the practice of simply adding finite amplitude effects and ground surface effects to find sound levels is not valid Linear extrapolations and techniques should only be used where linear acoustics are applicable.

14. SUBJECT TERMS

acoustics
acoustical blast waves
noise measurement
nonlinear acoustics
numerical analysis

15. NUMBER OF PAGES

16

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

FOREWORD

This research was conducted for the Office of the Chief of Engineers (OCE) under project 4A161102AT23, "Basic Research in Military Construction"; Work Unit NN-E30, "Wave Structure Interactions."

This research summarizes research results of the Ph.D. dissertation *A Finite Difference Numerical Model for the Propagation of Finite Amplitude Acoustical Blast Waves Outdoors Over Hard and Porous Surfaces*, University of Illinois, Urbana-Champaign, 1990, which details research performed for the Environmental Division (EN) of the U.S. Army Construction Engineering Research Laboratory (USACERL). The University of Illinois thesis advisor was Dr. Richard Raspet. Dr. Edward W. Novak is Acting Chief, USACERL-EN. The USACERL technical editor was Mr. William J. Wolfe, Information Management Office.

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

CONTENTS

MODELING NONLINEAR ACOUSTICAL BLAST WAVES OUTDOORS: A RESEARCH SUMMARY

1 INTRODUCTION

Background

The measurement and characterization of the impulse noise from blasts are critical to predicting the environmental impacts of military operations. One must take measurements close enough to a source to eliminate meteorological variations, but far enough away so that finite amplitude (nonlinear) wave effects do not dominate. In most cases, these measurements are made over natural outdoor surfaces. The effects of the finite impedance of the ground on the propagation of linear continuous waves are profound.

The techniques for predicting sound propagation outdoors using the infinitesimal pressure amplitude assumption, linear acoustic methods, are well established. The fast field program (the FFP)[1] and the parabolic equation method (PE method)[2] are the most prevalent computational approaches using the linear theory. However, these methods do not accurately model the physics of very loud sounds (over 150 dB), where the amplitudes of the pressure variations making up the sound become finite instead of infinitesimal, and the mathematics governing the sound propagation become nonlinear.

It is important to determine whether it is possible to model such loud sounds, such as the acoustic pulses from blasts. A computer model that simulates nonlinear blasts would allow researchers to better predict the impact of noise on communities surrounding Army training ranges. In addition, understanding the relation between very loud acoustic pulses and natural ground surfaces should aid in the interpretation of results from linear propagation prediction schemes.

Objectives

This report summarizes research conducted to: (1) devecop and test a numerical algorithm that could be used to model nonlinear acoustical blast waves, and (2) investigate the complicated relationship between nonlinear blast waves and natural ground surfaces for the purpose of sound propagation

---

[1] S J Frank and G W. Swenson, Jr., "A Brief Tutorial on the Fast Field Program (FFP) as Applied to Sound Propagation in the Air," *Applied Acoustics*, No. 27 (1989), pp 203-216; S.W. Lee, N. Bong, W.F. Richards, and Richard Raspet, "Impedance Formulation of the Fast Field Program for Acoustic Wave Propagation in the Atmosphere," *Journal of the Acoustical Society of America*, No. 79 (1986), pp 628-634; Richard Raspet et al., "A Fast Field Program for Sound Propagation in a Layered Atmosphere Above an Impedance Ground," *Journal of the Acoustical Society of America*, No. 77 (1985), pp 345-352.

[2] Kenneth E Gilbert and Michael J. White, "Application of the Parabolic Equation to Sound Propagation in a Refracting Atmosphere," *Journal of the Acoustical Society of America*, No. 85 (1989), pp 630-637; Michael J. White and Kenneth E. Gilbert, "Application of the Parabolic Equation to the Outdoor Propagation of Sound," *Applied Acoustics*, No. 27 (1989), pp 227-238.

prediction. The complete investigation is detailed in USACERL Technical Manuscript N-91/23.[3]

Approach

A mathematical analysis determined the proper numerical algorithm to correctly model the nonlinear acoustical blast waves. The numerical algorithm was implemented in a computer simulation, the results of which verified the algorithm. The simulation also provided numerical results for further investigation into the relationship between the nonlinear blast waves and the natural outdoor ground surfaces.

[3] Victor W Sparrow, *A Finite Difference Numerical Model for the Propogation of Finite Amplitude Acoustical Blast Waves Outdoors Over Hard and Porous Surfaces*, TM N-91/23 (U.S. Army Construction Enginering Research Laboratory [USACERL], July 1991).

2 METHODOLOGY

One cannot apply frequency domain analysis to the simulation of finite amplitude sound outdoors. The equations governing finite amplitude acoustic propagation are nonlinear, and thus require a time-domain solution. Furthermore, if the outdoor propagation is bounded by a porous medium such as the ground, the ground surface must be modeled in the time domain to couple to the air solution as well.

The numerical simulations developed in this research to model finite amplitude propagation outdoors use the method of finite differences to solve an initial-boundary value problem. A region in space is defined with boundaries in which the propagation equations are solved by specifying the region at a given time, and then by solving numerically for values in the region at future times.

Air Numerical Solution

The equations to model the finite amplitude acoustic propagation in the air (Eq 4.1 to 4.5)[4] involve the following acoustic variables: density, particle velocity, pressure, entropy, and temperature. This differs from linear sound propagation studies in which only one acoustic variable is used, usually pressure.

The equations include the effects of classical dissipation, a bulk viscosity, and all the second-order nonlinear terms which give rise to the finite amplitude behavior. The classical dissipation effects are heat conduction and shear viscosity, which for outdoor propagation are substantial but not the most significant contributors to attenuation of acoustic signals. The bulk viscosity enters the equations to account for high frequency relaxation effects. In this research, the bulk viscosity was increased appropriately to approximate the dominant absorption effects of oxygen and nitrogen relaxation in air.

Assuming a homogeneous atmosphere, it is possible to rewrite the equations in a form where only one time derivative exists in each equation (Eq 4.34 to 4.38). These manipulated equations are valid for amplitudes approaching the linear acoustic limit, while still accounting for all the dissipation and second-order nonlinear terms.

The manipulated equations are solved by a highly accurate finite difference method, a second-order in time and fourth-order in space MacCormack scheme.[5] Finding this method and applying it to the equations of acoustics was one of the breakthroughs in this research. The details of this method are again relegated to the thesis reported in USACERL TM N-91/23.

One additional enhancement (a fourth-order artificial viscosity) was made to the numerical solution to the air equations, which significantly improves the MacCormack results. A fundamental property of nonlinear interactions is that high frequency energy is created at the expense of the low frequencies. However, such high frequencies can be so high that the finite difference grid cannot resolve the frequencies well, and the numerical method becomes inaccurate. The additional artificial viscosity has

---

[4] All equation citations refer to Victor W. Sparrow, *A Finite Difference Numerical Model for the Propagation of Finite Amplitude Acoustical Blast Waves Over Hard and Porous Surfaces.*

[5] David Gottlieb and Eli Turkel, "Dissipative Two-Four Methods for Time Dependent Problems," *Mathematical Computation*, No. 30 (1976), pp 703-723.

a frequency dependance of omega to the fourth power and will dissipate very high frequency energy, while leaving the lower frequencies of interest unaffected.

Porous Ground Numerical Solution

The equations used to simulate a porous ground surface (Eq 5.12 to 5.14) use Attenborough's notation[6] and are derived under a low frequency assumption. The equations contain the parameters of porosity, flow resistance, and an effective density or structure factor, which Attenborough relates to the tortuosity.

The local reaction assumption is inherently built into this model of the porous ground surface. All propagation is assumed to be normal to the surface of the flat ground. One may visualize this as a porous medium made of cylindrical soda straws lined up to form the ground surface.

An analysis was performed to study the properties of this simulated porous medium. The medium exhibits a finite impedance with equal real and imaginary parts that decrease with increasing frequency, and an effective sound speed and absorption coefficient that increase with increasing frequency. These trends and the values are similar to those reported in measurements of real outdoor surfaces.

A second-order MacCormack finite difference solution, similar to that for the air equations, was used to solve these porous ground equations numerically. This method revealed a stability restriction on the size of the time step relative to the porosity, the flow resistance, and the structure factor. If the chosen time step was too large, the numerical method would become unstable.

Because the speed of sound in the pores of the ground is on the order of one-tenth of that same speed in air, the finite difference grid for the ground must be 10 times finer than for the air grid. An interpolation algorithm was used to interface the coarse air grid and the fine ground grid.

Initial Conditions

This research is primarily concerned with the simulation of impulsive-type sound sources. Therefore, as an initial condition, a pulse shape appropriate for a blast was used. This waveform is given in terms of acoustic pressure. From the acoustic pressure, it was possible to find a spherical potential and the other acoustic variables needed for an initial condition to the air propagation equations. The initial field was always assumed to be zero in the porous ground.

Using experimental data, appropriate pulse durations for various peak sound pressure levels were found by using scaling laws. These scaling laws are useful to derive rough approximations, but not to explicitly account for the absorption of the air or for ground impedance. By using the scaling laws, it was possible to take the blast data and find initial conditions for the sounds from an electric spark discharge.

---

[6] Keith Attenborough, "Acoustical Characteristics of Porous Material," *Journal of the Acoustical Society of America*, No. 82 (1982), pp 179-227.

Such a spark pulse was used instead of the blast waves for much of the verification of the algorithms for the numerical solutions.

Absorbing Boundary Conditions

The solution to the acoustical equations in this research is restricted to a finite domain because of limited computer memory. Since the outdoor environment is unbounded, an absorbing boundary condition was used to truncate the computational region while simulating an unbounded medium.

3 RESULTS

Algorithm Verifications

Several different types of tests were performed to validate the numerical model. The numerical solution was compared to the results of the Pestorius algorithm[7] for one-dimensional propagation of electric spark pulses in the free field. The Pestorius algorithm is another finite-amplitude acoustical-computer simulation method valid only for specific situations. There was close agreement between the two methods.

A second comparison was made for normal incidence of a spark pulse on a hard surface. In this case, the finite difference method was compared to an analytic result of Pfriem[8] for the pressure amplification at the hard surface as a function of the free-field incident peak pressure. Again, the agreement was good.

A third verification was based on the electric spark pulses reflecting obliquely from a hard surface. No prior computational or analytic results exist for this comparison. In this case, plots of pressure amplification near the hard surface versus incident angle turned out to be similar to such curves for blast data on a larger scale. These results do agree qualitatively with what is expected from physical arguments.

Blast Predictions

To use these numerical methods to investigate the interaction of blast waves with a natural outdoor surface, three types of regular runs were made. a run in the free field, a run with a hard surface, and a run for a particular porous surface. The chosen porous surface had a flow resistance of 300,000 mks Rayls, a porosity of 0.3, and a tortuosity of 1.5. The three types of runs were compared.

Two groups of simulations were performed. The first group of simulations involved a fixed charge weight where the height of the charge varied. This fixed weight would produce a peak sound pressure level of 180 dB, 30 m from the source. Curves of pressure amplification near the hard and porous ground as a function of incident angle were obtained from the runs. These plots were similar to the curves in the literature that are based on experimental observations.[9]

The second group of simulations involved keeping the geometry fixed, and the blast charge height at 1 m while changing the charge weight. Here the peak sound pressure levels 30 m from the source were 180, 174, 168, 162, 156, and 150 dB. Numerical receivers were placed at heights of zero, 1, 2, and 5 m

---

[7] Henry E. Bass, Jean Ezell, and Richard Raspet, "Effect of Vibrational Relaxation on the Rise Times of Shock Waves in the Atmosphere," *Journal of the Acoustical Society of America*, No. 74 (1983), pp 1514-1517.

[8] David T. Blackstone, "Nonlinear Acoustics (Theoretical)," *AIP Handbook*, 3d ed. (McGraw-Hill, N.Y., 1972), pp 3-203.

[9] S. Gladstone, ed., *The Effects of Nuclear Weapons*, rev. ed. (U.S. Atomic Energy Commission, April 1962), p 147, Gilbert F. Kinney and Kenneth J. Graham, *Explosive Shocks in Air*, 2d ed. (Springer Verlag, N.Y., 1985), p 82, C.W. Heaps, K.S. Fansler, and E.M. Schmitt, "Computer Implementation of a Muzzle Blast Prediction Technique," *The Shock and Vibration Bulletin*, No. 56 (Shock and Vibration Information Center, Naval Research Laboratory, Washington DC, August 1986), pp 213-228.

and distances of 30, 45, 60, 90, 120, 180, 240, 360, 480, 720, and 960 m from the source, to monitor the passage of the blast waves.

The propagation results over the hard surface showed that the peak sound pressure levels decayed at nearly the rate of $r^{-1.2}$, which agrees with the work of Reed[10] for weak shocks in the far field of a strong blast. However, for the porous ground surface, a different trend was found. At lower amplitudes, the peak sound pressure levels fell off faster than over hard surfaces, which would be expected for propagation over a porous medium in the linear acoustic limit. This phenomenon is called excess attenuation. At higher amplitudes, the peak level decay rate was less than the decay rate over the hard surface. These runs showed that the finite amplitude nonlinear effects of the higher amplitude blasts are likely, thereby decreasing the finite impedance effects of the natural ground surface. This is an important interaction not predicted by linear theory propagation programs.

[10] Jack W Reed, "Atmospheric Attenuation of Explosion Waves," *Journal of the Acoustical Society of America*, No. 61 (1977), pp 39-47.

4 CONCLUSIONS

This study developed a numerical method to model the nonlinear acoustical blast waves, and verified the method's performance. The method was a second-order in time and fourth-order in space version of the MacCormack finite difference scheme, which included a fourth-order artificial viscosity. The algorithm is stable and seems adaptable for a wide variety of nonlinear acoustics studies. In addition, absorbing boundary conditions were developed to allow for a numerical solution on a relatively small computational domain.

An investigation of the interaction between the finite amplitude blast waves and a natural ground surface determined that, as the finite amplitude effects are increased, the effect of a finite ground impedance is decreased. This relationship is nonlinear, and implies that the results of sound propagation and noise mitigation studies, based on any peak sound pressure levels over 156 dB and involving surface reflection, should also be nonlinear. This nonlinear relationship also implies that the practice of simply adding finite amplitude effects and ground surface effects to find sound levels is not valid.

Furthermore, in outdoor propagation studies, most finite amplitude effects occur near the sound source. Any data obtained 100 m from the source and subsequently referenced back to 1 m from the source, cannot be valid if the peak level at 1 m is over 156 dB. For blasts, the approximate method to perform such spatial extrapolations is to use the scaling laws. Linear extrapolations and techniques should be used only when linear acoustics are valid.

REFERENCES

Attenborough, Keith, "Acoustical Characteristics of Porous Material," *Journal of the Acoustical Society of America*, No. 82 (1982), pp 179-227.

Bass, Henry E., Jean Ezell, and Richard Raspet, "Effect of Vibrational Relaxation on the Rise Times of Shock Waves in the Atmosphere," *Journal of the Acoustical Society of America*, No. 74 (1983), pp 1514-1517.

Blackstone, T., "Nonlinear Acoustics (Theoretical)," *AIP Handbook*, 3d ed. (McGraw-Hill, N.Y., 1972), pp 3-203.

Frank, S.J., and G.W. Swenson, Jr., "A Brief Tutorial on the Fast Field Program (FFP) as Applied to Sound Propagation in the Air," *Applied Acoustics*, No. 27 (1989), pp 203-216.

Gilbert, Kenneth E., and Michael J. White, "Application of the Parabolic Equation to Sound Propagation in a Refracting Atmosphere," *Journal of the Acoustical Society of America*, No. 85 (1989), pp 630-637.

Gladstone, S., ed., *The Effects of Nuclear Weapons*, rev. ed. (U.S. Atomic Energy Commission, April 1962), p 147.

Gottlieb, David, and Eli Turkel, "Dissipative Two-Four Methods for Time Dependent Problems," *Mathematical Computation*, No. 30 (1976), pp 703-723.

Heaps, C.W., K.S. Fansler, and E.M. Schmitt, "Computer Implementation of a Muzzle Blast Prediction Technique," *The Shock and Vibration Bulletin*, No. 56 (Shock and Vibration Information Center, Naval Research Laboratory, Washington DC, August 1986), pp 213-228.

Kinney, Gilbert F., and Kenneth J. Graham, *Explosive Shocks in Air*, 2d ed. (Springer Verlag, N.Y., 1985), p 82.

REFERENCES (Cont'd)

Lee, S.W., N. Bong, W.F. Richards, and Richard Raspet, "Impedance Formulation of the Fast Field Program for Acoustic Wave Propagation in the Atmosphere," *Journal of the Acoustical Society of America*, No. 79 (1986), pp 628-634.

Raspet, Richard, et al., "A Fast Field Program for Sound Propagation in a Layered Atmosphere Above an Impedance Ground," *Journal of the Acoustical Society of America*, No. 77 (1985), pp 345-352.

Reed, Jack W., "Atmospheric Attenuation of Explosion Waves," *Journal of the Acoustical Society of America*, No. 61 (1977), pp 39-47.

Sparrow, Victor W., *A Finite Difference Numerical Model for the Propogation of Finite Amplitude Acoustical Blast Waves Outdoors Over Hard and Porous Surfaces*, TM N-91/23 (U.S. Army Construction Enginering Research Laboratory [USACERL], July 1991).

White, Michael J., and Kenneth E. Gilbert, "Application of the Parabolic Equation to the Outdoor Propagation of Sound," *Applied Acoustics*, No. 27 (1989), pp 227-238.

DISTRIBUTION

Chief of Engineers
ATTN: CEHEC-IM-LH (2)
ATTN: CEHEC-IM-LP (2)
ATTN: CERD-L
ATTN: CECC-P
ATTN: CECW
ATTN: CECW-O
ATTN: CECW-P
ATTN: CECW-RR
ATTN: CEMP
ATTN: CEMP-C
ATTN: CEMP-CE
ATTN: CEMP-E
ATTN: CEMP-EA
ATTN: CEMP-EI (2)
ATTN: CEMP-ZA
ATTN: CEMP-ZM (2)
ATTN: CERD
ATTN: CERD-C
ATTN: CERD-M
ATTN: CERM
ATTN: DAEN-ZCZ
ATTN: DAEN-ZCI
ATTN: DAEN-ZCM
ATTN: DAEN-ZCE

HQ USAF/LEEEU 20332

US Army Engr Divisions
ATTN: Library (14)

US Army Europe
ODCS/Engineer 09403
ATTN: AEAEN-FE
ATTN: AEAEN-ODCS

Aberdeen Proving Ground, MD 21010
ATTN: Safety Office Range Safety Div
ATTN: U.S. Army Ballistic Res Lab (2)
ATTN: ARNG Operating Activity Ctr
ATTN: Human Engineer Lab
ATTN: HSHB-MO-B (3)

Ft. Leonard Wood, MO 65473
ATTN: Canadian Liaison Officer
ATTN: German Liaison Staff
ATTN: British Liaison Officer (2)
ATTN: French Liaison Officer

US Military Academy 10996
ATTN: Facilities Engineer
ATTN: Dept of Geography & Environmental Engr
ATTN: Dept of Mathematics
ATTN: MAEN-A

USA AMCCOM 61299
ATTN: AMSMC-RI
ATTN: AMSMC-IS

AMC 22333
ATTN: AMCEN-A

Fort Belvoir, VA 22060
ATTN: Water Resource Center
ATTN: CECC-R
ATTN: NACEC-FB

CEWES 39180
ATTN: WESSEN-B
ATTN: Soils & Pavements Lab
ATTN: C/Structures

NAVAIRSYSCOM 20360
ATTN: Library

Little Rock AFB 72099
ATTN: 314/DEEE

NAVFAC 22332
ATTN: Code 2003

Naval Surface Weapons Center 22448
ATTN: N-43

Fort McPherson, GA 30330
ATTN: AFEN-FEB

U.S. Army Aeromedical Res Lab 36362
ATTN: SGRD-UAS-AS

Wright-Patterson AFB, OH 45433
ATTN: AAMRL/BB
ATTN: AAMRL/BBE

Fort Monmouth 07703
ATTN: AMSEL-EW-MD

WASH DC 20419
ATTN: Housing & Urban Dev (2)

Department of Transportation
ATTN: Library 20590

Naval Undersea Center, Code 401 92132

Bureau of National Affairs 20037

Building Research Board 20418

Transportation Research Board 20418

Federal Aviation Administration 20591

U.S. Army LABCOM
ATTN: SLCAS-AS-I 88002-5501
ATTN: SLCAS-AS-M 88002-5501

U.S. Department of the Interior
ATTN: Alaska Fish and Wildlife Research Center 99503

Picatinny Arsenal 07801

National Guard Bureau 20310
Installation Division

US Government Printing Office 20401
Receiving/Depository Section (2)

US Army Env. Hygiene Agency
ATTN: HSHB-ME 21010

Nat'l Institute of Standards & Tech 20899
ATTN: Force & Acoustics Group

Defense Technical Info. Center 22304
ATTN: DTIC-FAB (2)

99
09/91

This publication was reproduced on recycled paper.